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PRELIMINARY INVESTIGATION OF IMPACT ON MULTIPLE-SHEET STRUCTURES AND AN EVALUATION OF THE METEOROID HAZARD TO SPACE VEHICLES

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SUMMARY

Small pyrex glass spheres, representative of stoney meteoroids, were fired into 2024-T3 aluminum alclad multiple-sheet structures at velocities to 11,000 feet per second to evaluate the effectiveness of multisheet hull construction as a means of increasing the resistance of a spacecraft to meteoroid penetrations. The results of these tests indicate that increasing the number of sheets in a structure while keeping the total sheet thickness constant and increasing the spacing between sheets both tend to increase the penetration resistance of a structure of constant weight per unit area. In addition, filling the space between the sheets with a light filler material was found to substantially increase structure penetration resistance with a small increase in weight.

An evaluation of the meteoroid hazard to space vehicles is presented in the form of an illustrative example for two specific lunar mission vehicles, a single-sheet, monocoque hull vehicle and a glass-wool filled, double-sheet hull vehicle. The evaluation is presented in terms of the "best" and the "worst" conditions that might be expected as determined from astronomical and satellite measurements, high-speed impact data, and hypothesized meteoroid structures and compositions.

It was observed that the vehicle flight time without penetration can be increased significantly by use of multiple-sheet rather than single-sheet hull construction with no increase in hull weight. Nevertheless, it is evident that a meteoroid hazard exists, even for the vehicle with the selected multiple-sheet hull.

INTRODUCTION

Among the many problems besetting a space-vehicle designer is that of protecting the vehicle from damage from the impact of meteoroids. These pieces of cosmic debris travel at very high velocity and, on impact with a space vehicle, may completely puncture its thin-skinned, lightweight hull, even if the meteoroids are quite small. Fortunately, the number of meteoroids diminishes as their size increases so that the most likely damage to a vehicle is a small hole in the outer skin. They are numerous enough, however, that one must consider the possibility of a meteoroid large enough to rupture a hull extensively, thereby causing an explosive decompression, or to damage seriously the contents of a vehicle after piercing the skin. The chance of being struck increases, of course, with the size of the vehicle and the duration of the voyage.

The most straightforward method of protecting a vehicle from meteoroid penetration would be to make the outer skin from a single sheet of material thick enough to resist penetration by the largest meteoroids that would be encountered on the voyage, taking into account the size of the vehicle, the length of the flight, and the maximum probability of encounter allowed by the level of "reasonable risk" for the flight. This approach, however, would result in a vehicle of unacceptably large weight.

A more sophisticated approach would be to construct a double hull of sheets spaced a distance apart. The value of this approach has been recognized for many years in the design of armor for military vehicles (e.g., see ref. 1), although the application to spacecraft was first suggested by Dr. Fred L. Whipple of the Harvard College Observatory (ref. 2). Dr. Whipple proposed that the spacecraft be surrounded by a thin outer shell spaced a distance out from the main hull, which he called a "meteor bumper." He suggested that a meteoroid would vaporize on impact with the bumper (along with vaporization of some of the bumper material) and its ability to penetrate the hull would thereby be sharply reduced. On the other hand, the meteoroid may possibly just be fragmented on impact with the bumper and not vaporized. If this is the case, the cloud of meteoroid and bumper fragments will diverge laterally with distance behind the bumper. In this way, the kinetic energy of the meteoroid will not be concentrated in a single solid body but will be divided among the broken meteoroid and bumper fragments. The inner hull, because of the larger affected area, will then be more resistant to penetration by the smaller, less potent particles. The logical extension of this concept would be to employ a number of thin shells to provide possibly even more protection, the objective being to design a space structure having a high degree of resistance to total pentration in comparison to a single-hulled space structure of the same weight.

The purpose of this report is twofold. First, the results of the impact tests in the Ames Hypervelocity Ballistic Range are presented. These are tests of impact on multiple-sheet structures by projectiles representative of stoney meteoroids. Second, an evaluation of the meteoroid hazard to space vehicles is discussed on the basis of astronomical and space-probe measurements, high-speed impact data, and hypothesized meteoroid structures and compositions. In addition, the effectiveness of multiple-sheet structures in increasing resistance to structural penetration is estimated for a lunar mission vehicle.

NOTATION

A cross-sectional area of meteoroid, sq ft

C a constant, the product of the number of meteoroids and the meteoroid mass to the kth power

C_D drag coefficient of a body traveling at high velocity, 0.92

c speed of sound in target material, the velocity of propagation of a plane elastic wave along the axis of a slender prismatic bar, ft/sec

d diameter of spherical projectile, in.

j average visual intensity of radiation of a meteor, considered as covering the time of visibility of the meteor, visual ergs/sec

k exponent of the meteoroid mass in the number-mass relationship

L visible length of meteor trajectory, ft

m mass of meteoroids, grams

N number of impacts of meteoroids of mass m or greater, impacts/ft^2-day

p penetration, measured from original target surface, in.

R ratio of the measured ballistic limits between a multiple-sheet target and a single-sheet target of the same total sheet thickness

T duration of meteor visibility, sec

t total sheet thickness of multiple-sheet and single-sheet structures, in.

V velocity of projectile or meteoroid, ft/sec

β total meteor luminous efficiency, the fraction of initial meteor kinetic energy converted into visible light

ρ mass density, gm/cc

ρ_a mass density of atmosphere, slugs/ft^3

Subscripts

M multiple-sheet structure

P projectile

S single-sheet structure

t target

IMPACT TESTS ON MULTIPLE-SHEET STRUCTURES

Experimental Procedure

The experiment consisted of firing a projectile into a target placed in the target chamber of a free-flight range. The apparatus is illustrated in figure 1 and is described in detail in reference 3. The principal components are the gun, the blast tank, two velocity chambers, and a target chamber.

The projectiles were spheres of pyrex glass with a density of 2.23 gm/cc. This material was selected because it shatters upon impact and, thus, is believed to be representative of stoney meteoroids. The sphere diameters were 1/8 inch in all tests and were the smallest that could be accommodated in the range at that time. By using the minimum size of sphere, the laboratory tests approached the actual conditions of meteoroid impact as closely as possible, although the difference in scale is still around two orders of magnitude.

The spheres were fired from a powder gun at velocities to 8000 feet per second, and from a light-gas gun to higher velocities. Since the guns were 0.22 caliber, the spheres were fired in sabots which not only guided them down the bore of the gun barrel, but also protected them from the damaging effects of the propellant gases. The sabots were constructed so that they separated into four pieces on leaving the muzzle and were trapped in the blast tank.

In the velocity chambers, four pairs of spark photographs were taken of the spheres at locations spaced over 4 feet of their trajectory. Cycle-counter chronographs recorded the time at which each spark photograph was taken. These records provided measurements of time and distance along the trajectory, and the velocity at impact could be accurately determined from them. The spark photographs also showed the physical condition of the sphere in flight and established that the sphere had survived the firing undamaged and was flying true to the target.

The targets were multiple-sheet structures consisting of thin, 2024-T3 aluminum alclad sheets placed one behind the other. They were placed at the end of the target chamber (see fig. 1) and were alined with the front face normal to the projectile trajectory. In these tests, the number of sheets and the thickness of each sheet in a target were varied so that the sum of the thicknesses of all the sheets in each target had the same value of 0.062 inch throughout the series of tests. In this way, the weight per unit area of the aluminum sheets in all the targets was the same. The number of sheets was varied from one to four. Two spacings between the sheets were tested, 1/2 inch and 1 inch. In a particular multiple-sheet target all sheets had the same thickness (the value being adjusted according to the number so that the combined thickness equaled 0.062 inch) and the spacing between successive sheets was kept constant (1/2 inch or 1 inch).

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In one test, the effect of a filler material placed between the sheets was investigated. This filler consisted of fluffy, glass-wool batting, customarily used for building insulation. It was tried in only the two-sheet target with the 1-inch spacing. Actually, two glass-wool batts, each 1 inch thick in normal use, were placed between the aluminum sheets, and the two batts were then compressed to a 1-inch total thickness. The weight per unit area of the target in this particular case was 30 percent greater than in the other tests of the program because of the weight of the filler material.

Experimental Results

The penetration resistance of a multiple-sheet structure is measured by its "ballistic limit" in these tests. The ballistic limit is a term taken from ordnance usage and is defined as "The particular velocity, ...determined by test, at which the plate," (the multiple-sheet structure in the present tests) "will just resist complete penetration by the projectile in question." (See ref. 4.) It is believed to be a good criterion for impact research on the meteoroid hazard to spacecraft because the craft's hull must maintain a completely tight enclosure throughout the voyage.

The results of the impact tests are shown in figure 2 with the ballistic limit plotted as ordinate, the number of sheets in the target as abscissa, and the spacing between sheets as an independent parameter. The ballistic limit for the target with the glass-wool filler is also plotted on this graph.

It can be seen that the penetration resistance of the structure is increased by a factor of 1.75 when the single sheet of material is divided into two sheets, each half as thick as the original, and spaced 1/2 inch apart. When the spacing between the sheets is increased from 1/2 to 1 inch, the penetration resistance is increased by about a factor of 1.25

or by a factor of abcut 2.2 over a single sheet of material of the same total thickness. Increasing the number of sheets comprising the structure from two to four with each sheet now one-fourth as thick as the original also increases the structure's ballistic limit. It can be seen that the four-sheet structures are about 1.2 times as effective as the two-sheet structures for both the 1/2-inch and 1-inch sheet spacings. Consequently, increasing the number of sheets from one to two is considerably more effective than increasing the number of sheets from two to four. In addition, it can be seen that the two-sheet structure with the 1-inch spacing is actually more resistant to penetration than the four-sheet structure with the 1/2-inch spacing. When fabrication ease and total structural weight, including members to hold the various sheets at their required locations, are considered, it seems apparent that two-sheet structures are probably the most efficient multiple-sheet structures.

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The most substantial gain in penetration resistance is achieved by filling the void between the sheets with a glass-wool filler. For the one case investigated, namely, a two-sheet structure with a sheet spacing of 1 inch, the penetration resistance of the structure with the glass-wool filler is about twice as great as that of the structure without the filler material and about 4.4 times greater than that of a single sheet of material of the same total-sheet thickness. It should be emphasized, however, that the weight of the glass-wool-filled structure is 30 percent greater than that of the other structures tested in the program.

Since the ballistic limit of a structure is the criterion for evaluating the penetration resistance of a structure, the penetration resistance can also be expressed in terms of the projectile kinetic energy that can be absorbed by a structure. The kinetic energy of the projectile is plotted against the number of sheets of a structure in figure 3 corresponding to the plot in figure 2. It can be seen that the two-sheet structure with the glass-wool filler and the 1-inch sheet spacing is capable of absorbing 20 times the projectile kinetic energy that can be absorbed by a single sheet of material of the same total-sheet thickness, or 15 times per unit weight, since the glass-wool-filled structure was heavier.

EVALUATION OF METEOROID HAZARD TO SPACE VEHICLES

The hazard that a spacecraft faces from meteoroids depends on the probability of the craft being struck by a meteoroid large enough to do significant damage. This probability depends, in turn, on the meteoroid distribution, velocities, structure, composition and penetration capabilities, and the spacecraft structure, size, and mission. These factors, then, must be considered in an evaluation of the meteoroid hazard in space.

This evaluation of the meteoroid hazard is undertaken as an illustrative example because it is clear from the outset that the results will apply strictly only to the particular craft and mission chosen. The purpose here is to seek an answer to the question: "Is the meteoroid hazard serious enough to be considered in the design of a spacecraft?" It is believed that a representative example will provide a partial answer, at least. The analysis that follows will be based on a hypothetical vehicle designed for a manned flight to the moon and return.

In assessing the damage of meteoroid impact one must first specify what is meant by "significant damage." This will be defined as a "complete puncture of the vehicle hull."

Two designs of outer hull structure will be considered. One is a single, constant-thickness skin; this is believed to be the simplest type of structure one might use to preserve the so-called "shirt sleeve" environment desired for manned spacecraft. The other is a double hull consisting of two equal-thickness skins separated by a space loosely filled with glass-wool insulation; this is the structure giving the greatest resistance to a penetration for a given weight per unit area in the tests reported in a previous section. Although it is considerably better than a monocoque hull, the double hull may still be far from the "optimum" structure (giving the greatest penetration resistance for a given weight). However, it will serve in the example as a "first step" in the development of effective structures for minimizing the meteoroid hazard.

Meteoroid Distribution

Our knowledge of meteoroids comes from three sources: (1) meteorites recovered from the surface of the earth; (2) observations of meteors visually, with photographic cameras, and by radar; and (3) direct measurement of meteoroid impacts by satellites and space probes. The trajectories and velocities of meteoroids in space are determined directly from the meteor observations. Their masses are determined indirectly from the same records through use of their atmospheric deceleration or their meteoric luminosity. The distribution of meteoroids in space and, in particular, the number of meteoroids of a given mass crossing a unit area per unit time can be estimated from meteor observations made at various locations over extended periods of time. It is found in references 5 and 6 that the mass-number relation may be expressed by the equation

$$Nm^k = C \tag{1}$$

where N is the number of meteoroids of mass m or larger, C is a constant, and k is an exponent having a value near unity. The values given to k and C vary somewhat from one observer to another. Whipple in reference 5 gives $k = 1$ and $C = 5.4\times10^{-9}$ (for m in grams and N

in number per square foot per day). Hawkins and Upton in reference 6 give $k = 4/3$ and $C = 5.1 \times 10^{-9}$.

The direct measurement of meteoroid impacts by rockets and artificial earth satellites has also been utilized to determine the distribution of meteoroids in space (see refs. 7 and 8). The impact measuring instrumentation for most space experiments has consisted of either wire grids or meteoroid momentum-sensitive plates. The wire-grid technique requires that the meteoroid strike one of the elements in the wire grid such that the circuit resistance and, hence, the telemetered signal will be altered after impact. This technique is limited by the fact that only the number of impacts is recorded and the indication of meteoroid size or mass is restricted to an estimate of the smallest meteoroid capable of severing a wire on impact. The momentum plate technique, on the other hand, is believed to be sensitive to the meteoroid momentum. When the plate is struck by a meteoroid, a crystal mounted on the back of the plate is strained and a signal is produced. However, the correlation between the signal magnitude and the meteoroid momentum for actual meteoroid impacts has not been made in the experiments to date. Any signal above the minimum sensitivity of the plate is recorded as a "count" and the momentum plate thus provides data similar to the wire grids in recording the total number of meteoroids with momentum greater than the threshold response of the instrument.

The rocket and satellite data have been analyzed to obtain the value of C in equation (1) assuming that $k = 1$. The minimum value of mass recorded in each experiment was determined from estimates of the instrument sensitivity (assuming an average meteoroid velocity of 98,400 feet per second). The results are tabulated in table I, which lists the vehicle, the launch date, the minimum mass sensitivity of the recording device, and the value of C obtained as the product Nm.

The assumption that $k = 1$ was tested by extrapolating the meteor observations of N and m ($m \geq 10^{-4}$ grams) to the values recorded in the satellite experiments ($m \geq 10^{-10}$ grams). It was found that $k = 1$ brought the satellite and meteor data into the best agreement. Other investigators have reached the same conclusion: Jonah (ref. 9) gives $k = 1$; Broyles (ref. 10) gives $k = 1.09$; Bjork (ref. 11) gives $k = 10/9$.

The data in table I, together with the meteor observations, give an average value of $C = 2 \times 10^{-8}$ (grams times impacts per square foot per day). Inspection of all the meteoroid data in table I, however, shows that the values of C range (with certain exceptions) an order of magnitude larger and smaller than the average, that is, $2 \times 10^{-7} < C < 2 \times 10^{-9}$. This variation is believed to be a fair estimate of the uncertainty in our present knowledge of the numbers and sizes of meteoroids. It would be misleading to pretend that our knowledge of the meteoroid distribution is more precise than this or to use an average value of C without clearly stating its upper and lower limits. Because the variation in C is such a critical factor in evaluating the meteoroid hazard, it was decided to use two values of C, the upper and lower limits, rather than an average. Consequently, this evaluation will consider a region of meteoroid distributions bounded by an optimistic distribution of $Nm = 2 \times 10^{-8}$ and a pessimistic distribution of $Nm = 2 \times 10^{-7}$, shown by the two plots of m versus N in figure 4. It should be noted that these distributions consider only sporadic meteoroids and do not include those meteoroids associated with predictable meteor showers.

Meteoroid Velocities

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The observations of meteors as they enter the earth's atmosphere have enabled astronomers to make a number of statements as to the origin of, and hence, the velocities of meteoroids. Whipple in reference 5 says, "Practically all photographic meteors are of cometary origin. The hyperbolic content, if present at all, is below 1 percent and the contributions by asteroidal material appear to be relatively small, if present. It seems relatively safe to extrapolate this conclusion to smaller bodies in space in view of arguments concerning both the observed and theoretical distributions of particle sizes." Since the meteoroids of interest here seem to be members of the solar system, their velocities are limited to a minimum of 36,000 ft/sec due to the earth's gravitational field and to a maximum of 236,000 ft/sec, which is the maximum velocity relative to the earth, attainable at the earth's distance from the sun by a particle which is a member of the solar system. It has been observed (ref. 5) that, "A velocity of 28 km/sec" (91,900 ft/sec) "is average for photographic meteors. Undoubtedly the velocity falls off for smaller meteoroids as we deal more and more with particles whose orbital eccentricities and dimensions have been reduced by physical effects ...." Data relating meteoroid mass and meteoroid velocity are presented in table I of reference 5 and are presented as figure 5 of this report. The velocities corresponding to specific meteoroid masses will be used according to these data in the evaluation presented in this report.

Meteoroid Structures and Composition

Until recently, it was thought that all meteoroids were compact stoney or iron-nickel bodies similar to meteorites found on the surface of the earth. However, photographic observations of the 1946 Draconid meteor shower by Jacchia, Kopal, and Millman (ref. 12) indicated that Draconid meteors were not ordinary meteors. It was observed that the meteoroid masses calculated from drag considerations did not agree with the masses calculated from luminosity considerations. Specifically, it was observed that "...the Draconid meteors emitted at least one hundred times more luminous energy per unit mass than ordinary meteors do." This discrepancy led the observers to conclude that "...the Draconid meteors of October 10, 1946, were composed of softer material, more easily melted or vaporized than ordinary meteors." With this fact in mind, Fred L. Whipple (ref. 5) proposed a porous dustball type of meteoroid with a density of 0.05 gm/cc which, in effect, increased the "dynamic" masses to agree with the "photometric" masses (see appendix A). He attributes the very low density meteoroids (dustball meteoroids) to those produced during the disintegration of comets. From his icy-conglomerate model of the core of a comet (ref. 13), he suggests that vaporization of the frozen gases in the comet core could result in a meteoroid with a highly porous structure.

Ernst Öpik, in reference 14, suggests another type of meteoroid structure. Öpik considers the meteoroid to be made up of many tiny bits of stone, each with a density of 3.5 gm/cc. However, he considers these grains of stone to be spaced in such a way that the over-all density of the meteoroid is still quite small.

Another meteoroid concept has been presented by B. Iu Levin in reference 15. Levin contends that meteoroid fragmentation accounts for the observed discrepancies between dynamic and photometric masses since dynamic mass measurements are calculated from the observed decelerations of individual meteoroid fragments, whereas the photometric mass measurements are determined from observations of the total meteoroid mass. Levin states, "However, the minuteness of the dynamic masses of meteoroids is a result of partial fragmentation, not of the minuteness of their densities."

Finally, there are the solid iron-nickel meteoroids, those bodies which are believed to come from that region of space called "the asteroid belt." These bodies, however, occur quite infrequently, so rarely in fact, that they will not be considered here (see refs. 5, 9, 10, 11, and 14).

Meteoroid Penetration Capabilities

The design of a spacecraft structure requires a general knowledge of the variation of penetration resistance when the structure is changed and the conditions of impact are varied. The limited data from the tests of this report cannot supply this information directly. Not only were the target configurations very few but also the ballistic limit gives only a measure of the penetration resistance for one projectile at one velocity. On the other hand, a fair knowledge does exist for "thick" targets, that is, for metal sheets where thickness is great compared to the depth of an impact crater. Furthermore, tests at the Langley Research Center have established a relation between the thickness of a "thin" plate and the depth of a crater in a "thick" plate produced by a projectile fired at the ballistic limit of the thin plate (ref. 16). This relation combined with the thick target data gives us the key to the design of the spacecraft structure.

The effect of meteoroid impact on the thin, single or multisheet structure is analyzed in the following manner. One first computes the depth of the crater, p, produced in a "thick" 2024-T3 aluminum alclad sheet by a spherical meteoroid of density, ρ_P, mass, m, and velocity, V, from the penetration formula presented in reference 17.

$$p = 2.83 m^{1/3} \rho_P^{1/3} \left(\frac{V}{\rho_t c}\right)^{2/3} \tag{2}$$

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where c is the bar speed of sound in the aluminum (c = 16,800 ft/sec). Next, one computes the thickness of the single sheet, t, that the meteoroid would have just perforated at velocity V from the relationship given in reference 16, namely,

$$t = 1.5p \tag{3}$$

Finally, one goes from single-sheet to multisheet structures by making the assumption that the ratio, R, of the ballistic limits obtained from the tests of this report holds for all conditions of impact, namely,

$$\frac{V_M}{V_S} = R = \text{constant} \tag{4}$$

where V_M is the ballistic limit of the multiple-sheet target and V_S is the ballistic limit of the single-sheet target. Since the ballistic limit is defined as the velocity at which complete target penetration is just prevented, formulas (2), (3), and (4) can be combined to give a formula for the minimum mass of meteoroid which endangers the spacecraft, namely,

$$m = \frac{t_S^3 R^2}{76.5 \rho_P (V/\rho_t c)^2} \tag{5}$$

where t_S is the thickness of the single-sheet target whose ballistic limit is 1/R of the multiple-sheet structure. If only a thin, single sheet is the target, it is clear that R = 1 and $t_S = t$.

A unique problem arises when an Öpik granular cluster meteoroid is considered. Substitution of 0.05 gm/cc for the density of the granular cluster into formula (2) indicates that the damage resulting from the impact of this meteoroid will be very slight. On the other hand, if this meteoroid is considered to be a nonhomogeneous body consisting of a number of grains of stone, each with a density of 3.5 gm/cc, spaced so that the over-all meteoroid density is 0.05 gm/cc, then the resulting damage can be quite severe, depending upon the interaction between the individual meteoroid grain impacts. Since this grain interaction factor is unknown, it is not feasible to calculate granular cluster damage at this time. Consequently, it will be assumed that the meteoroids of interest in this analysis can be represented by dustball meteoroids and solid stoney meteoroids. Iron-nickel meteoroids will be neglected because of their relative scarcity.

In applying the meteoroid damage factors to an evaluation of the meteoroid hazard to spacecraft, it must be remembered that two meteoroid distributions (an optimistic distribution and a pessimistic distribution) were selected for analysis in the meteoroid distribution section of this report. Thus, the most realistic combinations of meteoroid types and meteoroid distributions will give upper and lower limits to the meteoroid hazard. The pessimistic distribution and the pessimistic type of meteoroid, solid stoney, were combined to give the upper limit as a pessimistic "outlook," and the optimistic distribution with the optimistic type of meteoroid (the dustball) to give a lower limit or an optimistic "outlook." Thus, a range of meteoroid hazards will be presented into which the actual meteoroid hazard may be expected to fall. In all cases, the meteoroid velocities used will correspond to the selected meteoroid masses according to figure 5.

Evaluation of Meteoroid Hazard for Lunar Vehicle With Single-Sheet, Monocoque Hull

To illustrate the meteoroid hazard in space, the number of penetrations and the probability of vehicle puncture will be evaluated for a hypothetical space vehicle with monocoque-hull construction on a manned lunar voyage of 14 days. The effectiveness of multiple-sheet hull construction will then be evaluated by comparing the number of penetrations and the probability of vehicle puncture for a vehicle with this type of hull against those of the vehicle with monocoque-hull construction. The immediate problem, then, is to select the designs so that these evaluations and comparisons can be made.

First, let us consider the experimental data presented in this report. The choice of multiple-sheet hull designs is restricted to one of the structures investigated in this series of tests. From the test results shown in figures 2 and 3, it is obvious that the "best" structure investigated consists of two 1/32-inch sheets of 2024-T3 aluminum alclad spaced 1 inch apart and the space between the sheets filled with glass wool. If the vehicle shape is arbitrarily selected as a right circular cylinder with dimensions appropriate for a two-man vehicle and the hull material is 2024-T3 aluminum alclad with a working stress of 20,000 pounds per square inch, then the thickness of a single sheet of aluminum required to hold a vehicle internal pressure of 1 atmosphere is found to be 0.033 inch. This sheet thickness then will have to be the thickness of the inner sheet of a multiple-sheet hull. Consequently, the structure tested in the multiple-sheet impact tests (with inner and outer sheet thicknesses of 1/32 inch) is seen to be a hull structure that is also practical in terms of vehicle structural requirements. Thus, the multiple-sheet hull design evaluated here will consist of two 0.033-inch sheets of 2024-T3 aluminum alclad sheets, spaced 1 inch apart, with the space between the sheets filled with glass wool. The hull weight of this vehicle is about 384 pounds.

The selection of the sheet thickness for the monocoque-hull vehicle must now be made so that a reasonable comparison can be made between the two designs. It is thought that the most informative comparison between these designs can be made if the two vehicle hulls have equal weight per unit area. This criterion, then, determines the sheet thickness of the single-sheet hull vehicle to be 0.090 inch. This single-sheet hull design can now be used to evaluate the meteoroid hazard in space.

Figure 6 presents a plot of the number of penetrations versus the vehicle flight duration in days for the vehicle with the single-sheet monocoque hull for both the optimistic and pessimistic meteoroid hazard outlooks. It can be seen that for this vehicle hull design the vehicle will be penetrated once every 1840 days (once in every 131 lunar missions) if the optimistic meteoroid hazard outlook holds. If the pessimistic meteoroid hazard outlook is the case, then the vehicle will be penetrated about three times a day (43 times per lunar mission). In terms of penetration probability, the optimistic outlook gives a probability of penetration in one lunar mission of 0.76 percent, and the pessimistic outlook gives a probability of penetration in one lunar mission of more than 99.99 percent. Thus, it is seen that, for this design at least, a meteoroid hazard does exist.

Evaluation of Meteoroid Hazard for Lunar Vehicle With Spaced, Glass-Wool-Filled, Double-Sheet Hull

The effectiveness of multiple-sheet hull design in reducing the meteoroid hazard to space vehicles can now be illustrated by evaluating the number of penetrations and the penetration probability of the selected multiple-sheet hull design and comparing them against those of the single-sheet hull vehicle.

Plotted in figure 7 is the number of penetrations versus the vehicle flight duration for the multiple-sheet hull vehicle for both the optimistic and pessimistic meteoroid hazard outlooks. If the optimistic meteoroid hazard outlook holds, then this vehicle will be penetrated about once every 57,000 days (once in every 4,070 lunar missions). However, if the pessimistic meteoroid hazard outlook is the case, then the vehicle will be penetrated once every 11 days. Expressed in terms of probability of penetration in the 14-day voyage, the optimistic outlook gives a probability of 0.025 percent and the pessimistic outlook gives a probability of 72.34 percent.

The effectiveness of the multiple-sheet design can now be evaluated by comparing the penetration probabilities and the number of penetrations of the multiple-sheet and single-sheet designs. If the optimistic outlook holds, then the number of penetrations has been decreased from 1 in every 5 years for the single-sheet design to 1 in every 156 years for the multiple-sheet design. The penetration probability is decreased from 0.76 to 0.025 percent. Now, if the pessimistic outlook holds, the number of penetrations is reduced from 3 per day for the single-sheet design to 1 every 11 days for the multiple-sheet design. The penetration probability is decreased from more than 99.99 to about 72.5 percent. Expressed in another way, the effective flight time without penetration of the vehicle is increased by a factor of 35 with the multiple-sheet design. Even so, it is clear that a meteoroid hazard still exists even for a vehicle with multiple-sheet hull construction, particularly if the pessimistic meteoroid hazard outlook represents the actual conditions in space. Although it may seem unnecessarily conservative to assume that this condition does exist in space, our knowledge of the situation at the present time prohibits us from doing otherwise. Any other recourse could be disastrous to the occupants and mission of the space vehicle.

It should be noted that the multiple-sheet design presented in this report is probably very far from an optimum design. It is thought that other designs having much greater resistance to penetration can be developed.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., May 8, 1961

APPENDIX A

REDUCTION OF METEOR DATA TO OBTAIN THE METEOROID MASS

Photographic meteor observations can precisely determine such quantities as velocity, trajectory, deceleration, and luminous intensity. From these measurements, it is possible to calculate the mass of the meteoroid in two ways. First, the "dynamic" mass can be determined from the deceleration of the meteoroid as it enters the earth's atmosphere and, second, the photometric mass can be determined from the measured meteoroid luminosity.

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DYNAMIC MASS CALCULATIONS

The drag of a meteoroid as it enters the earth's atmosphere can be expressed, in terms of the meteoroid deceleration, as:

$$m\left(\frac{dV}{dT}\right) = -7.3\times10^{3} C_D \rho_a V^2 A \tag{A1}$$

With the assumption that the meteoroid is spherical in shape,

$$m = \frac{16.39\ \pi d_p^3}{6}\ \rho_p \tag{A2}$$

$$A = 6.944\times10^{-3}\left(\frac{\pi d_p^2}{4}\right) \tag{A3}$$

Substituting (A2) into (A3) gives

$$A = 1.076\times10^{-3}\left(\frac{\pi}{4}\right)\left(\frac{6m}{\pi\rho_p}\right)^{2/3} \tag{A4}$$

Substituting (A4) into (A1) and rearranging gives

$$m^{1/3}\rho_p^{2/3} = -\frac{15.72\ \pi}{8}\left(\frac{6}{\pi}\right)^{2/3}\frac{C_D \rho_a V^2}{dV/dT} \tag{A5}$$

Since the meteoroid's velocity, deceleration, and altitude (hence, the air density) can be directly measured and the drag coefficient of a body traveling at high velocity can be taken as 0.92, then the product $m^{1/3}\rho_p^{2/3}$ can be determined from equation (A5). If a meteoroid density is assumed, then the meteoroid mass can be calculated or, conversely, if a meteoroid mass is assumed, then the meteoroid density can be calculated.

PHOTOMETRIC MASS CALCULATIONS

The luminous efficiency of a meteor is defined as the fraction of the total meteoroid kinetic energy that is converted into visible light. This quantity can be expressed as:

$$\beta = 1.4734 \times 10^{-7} \frac{jT}{mV^2} \tag{A6}$$

Values for the luminous efficiency of meteors have been calculated in great detail by Öpik in reference 14 (among others), taking into account meteor ablation and vaporization, as well as the interactions between atomic particles. From calculations such as this, astronomers feel that the luminous efficiency of meteors has been accurately determined.

From the photographic observation of a meteor it is possible to determine the product jT directly from the following equation.

$$jT = \int j\left(\frac{dL}{V}\right) \tag{A7}$$

Consequently, the meteoroid mass is the only unknown quantity in equation (A6).

Determination of the meteoroid mass from equations (A6) and (A7) and substitution of the value for this quantity into equation (A5) leads to a solution for the meteoroid density.

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A
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TABLE I.- SUMMARY OF ROCKETS AND SATELLITE METEOROID MEASUREMENTS

Vehicle	Date	Mass sensitivity, m, grams	Nm, grams times impacts per day per ft^2 of mass m or greater
Explorer I	2-1-58	8×10^{-10}	5.4×10^{-8}
Explorer III	3-26-58	2.5×10^{-9}	9.0×10^{-9}
Sputnik III	5-15-58	1.1×10^{-8}	4.4×10^{-8}
Pioneer I	10-10-58	$\sim 10^{-10}$	3.2×10^{-9}
Pioneer II	11-8-58	10^{-10}	4.9×10^{-6}
USSR SRI	1-2-59	3.3×10^{-9}	6.1×10^{-8}
Explorer VI	8-8-59	1.7×10^{-8}	4.5×10^{-8}
USSR SRII	9-12-59	2×10^{-8}	1.5×10^{-8}
Vanguard III	9-18-59	3.3×10^{-9}	4.5×10^{-8}
USSR SRIII	10-4-59	1.3×10^{-9}	3.1×10^{-8}

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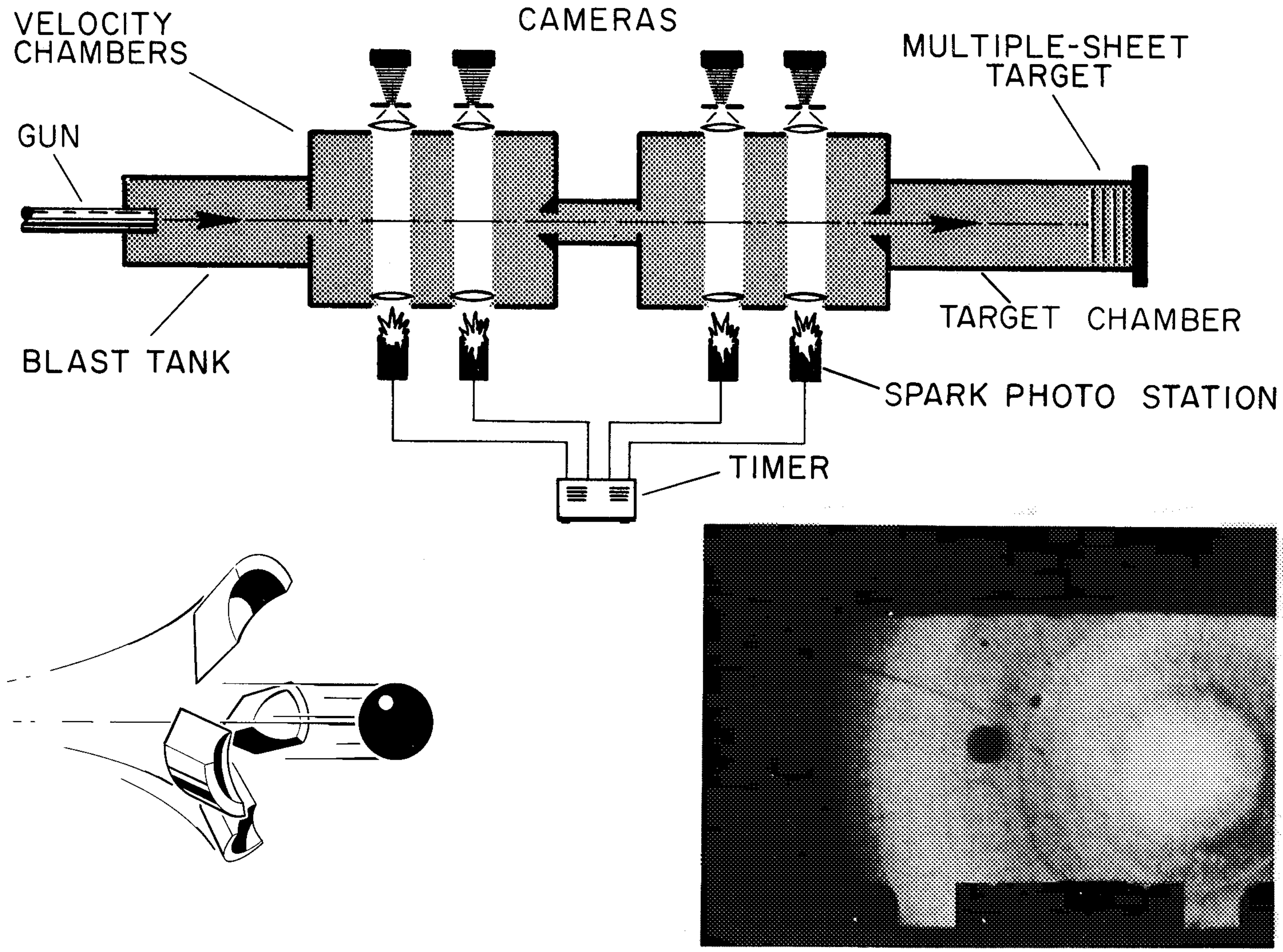

MODEL AND SABOT

SPARK PHOTO

Figure 1.- Test apparatus.

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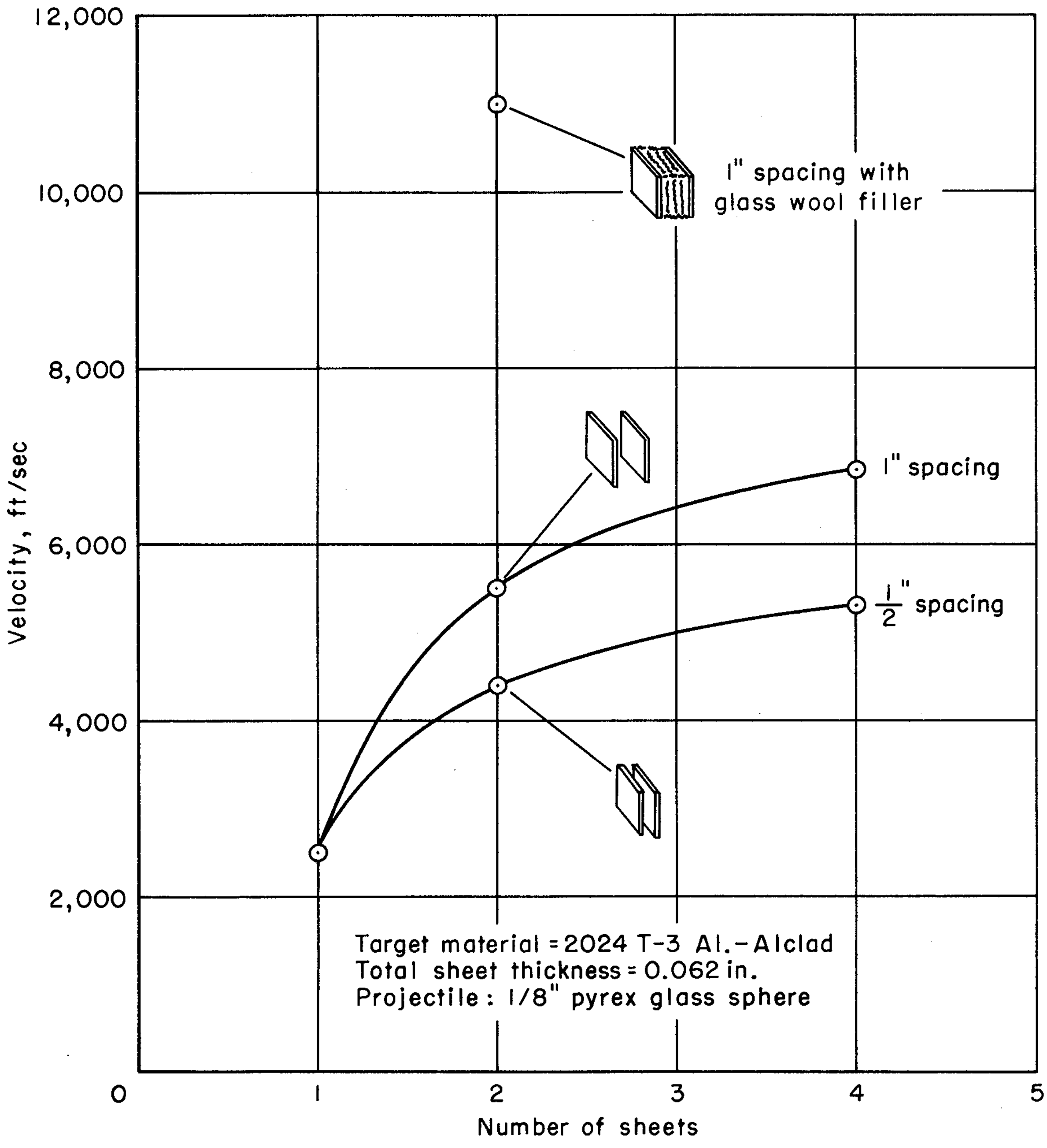

Figure 2.- Variation of target ballistic limit as a function of number of sheets.

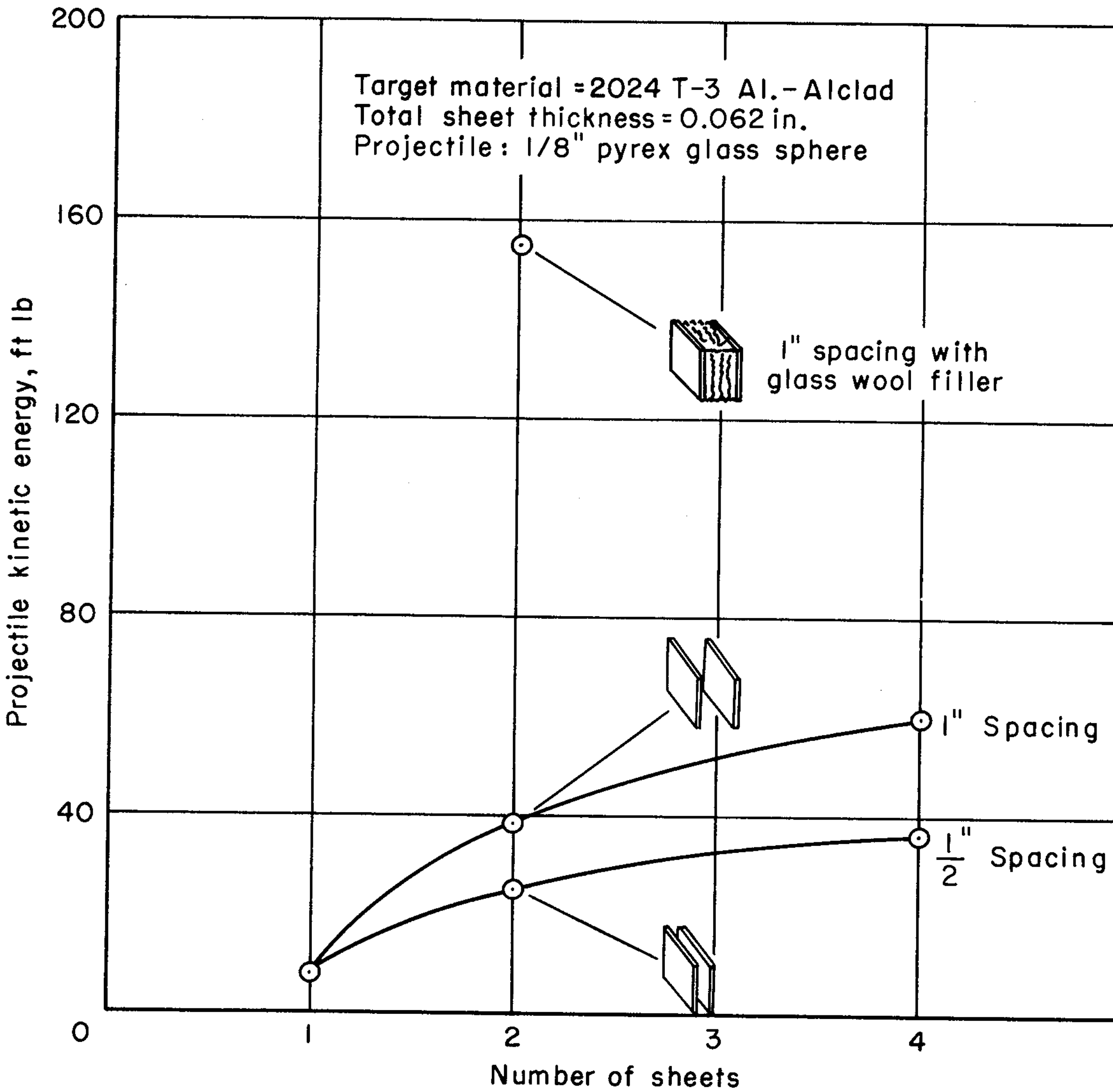

Figure 3.- Variation of projectile kinetic energy as a function of number of sheets.

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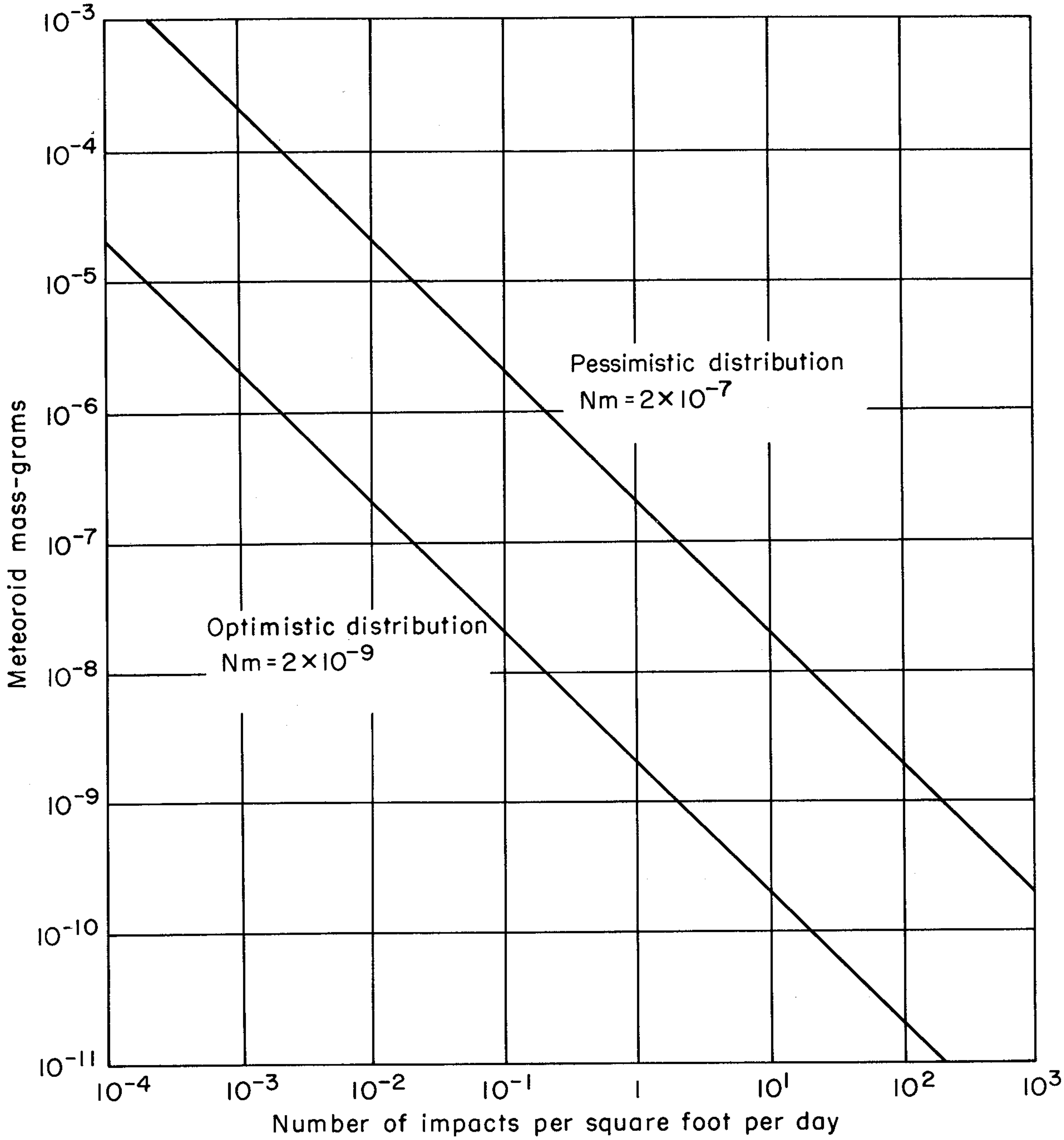

Figure 4.- Meteoroid mass-number distribution.

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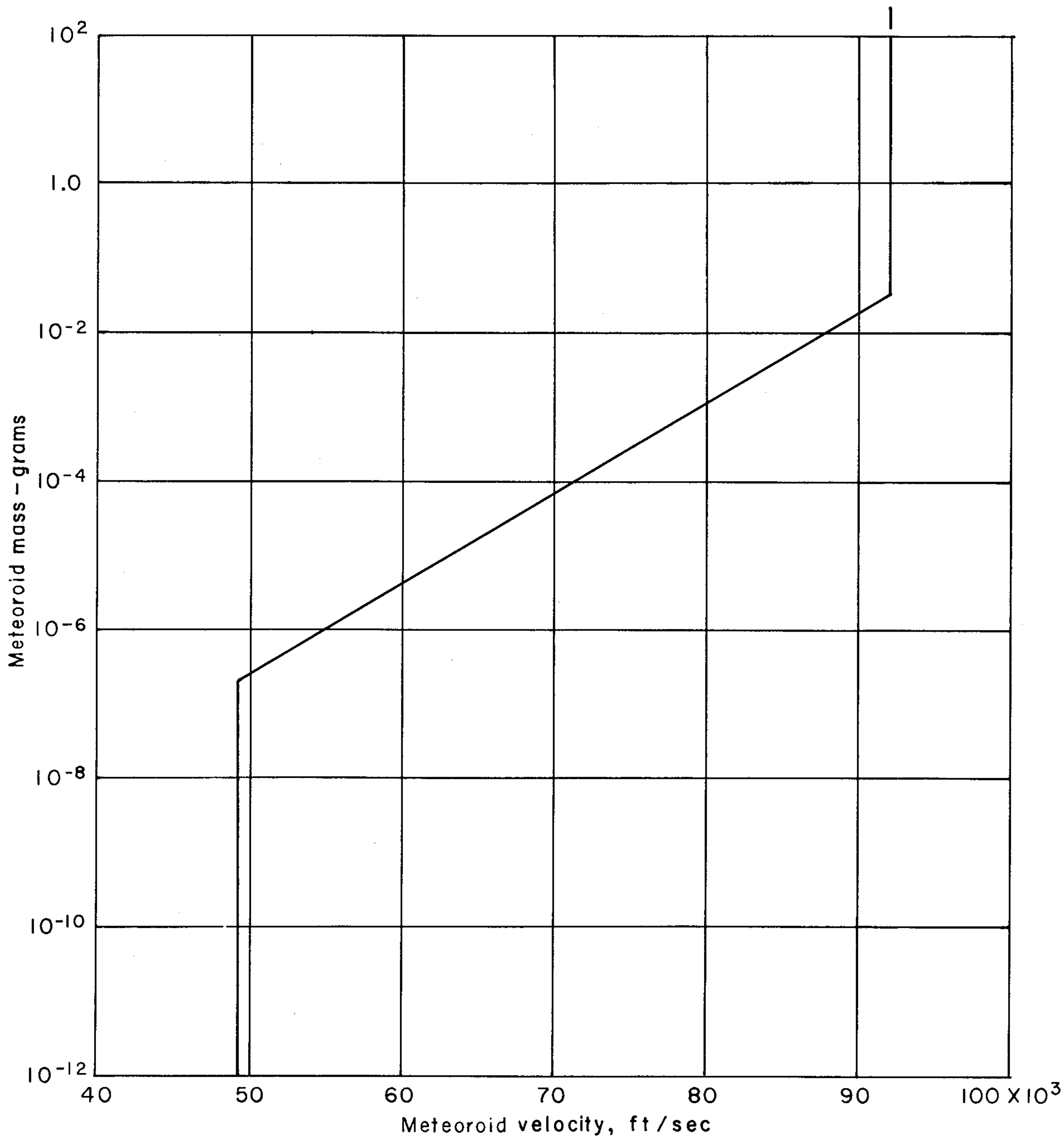

Figure 5.- Meteoroid mass-velocity distribution.

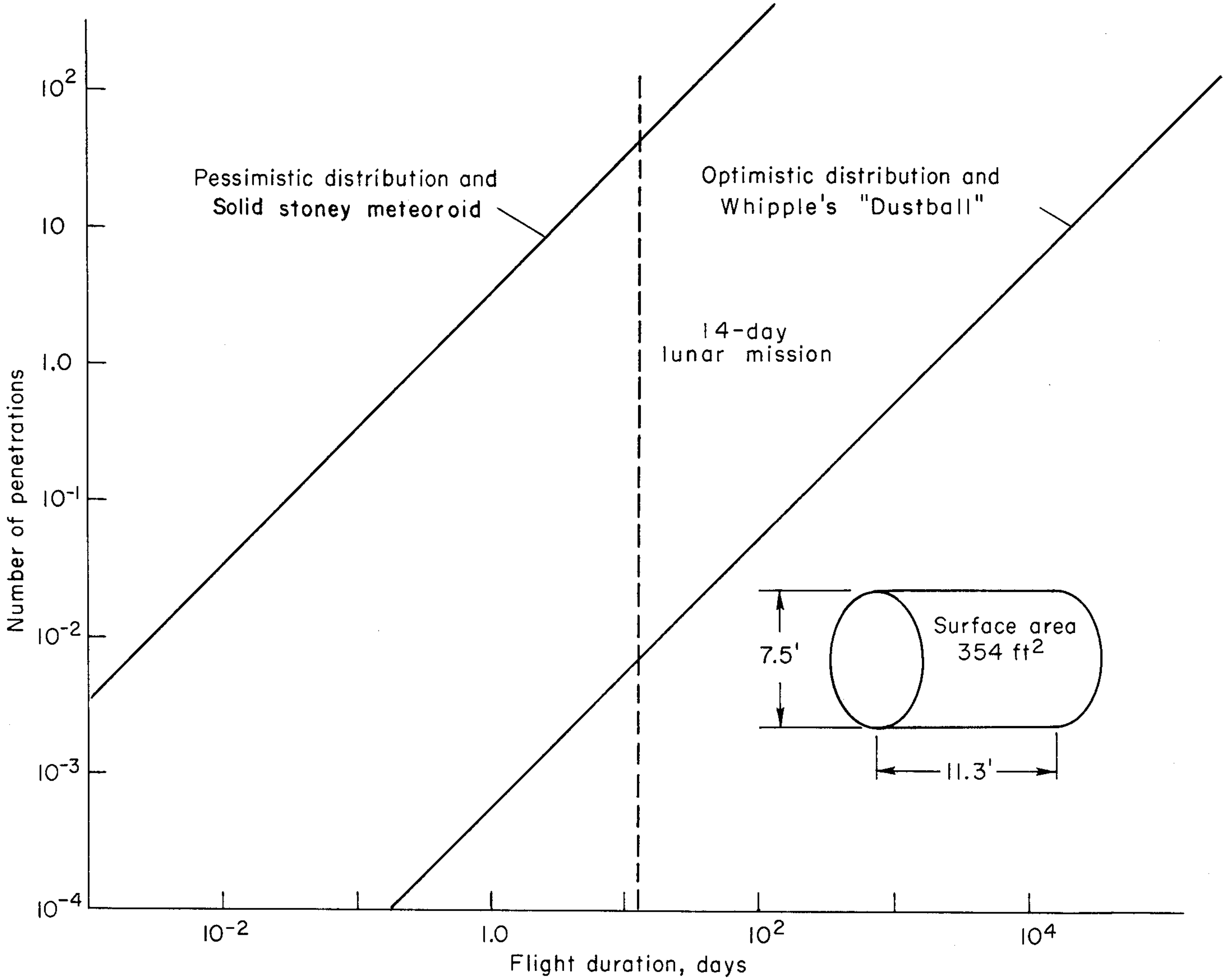

Figure 6.- Lunar vehicle with single-sheet, monocoque hull.

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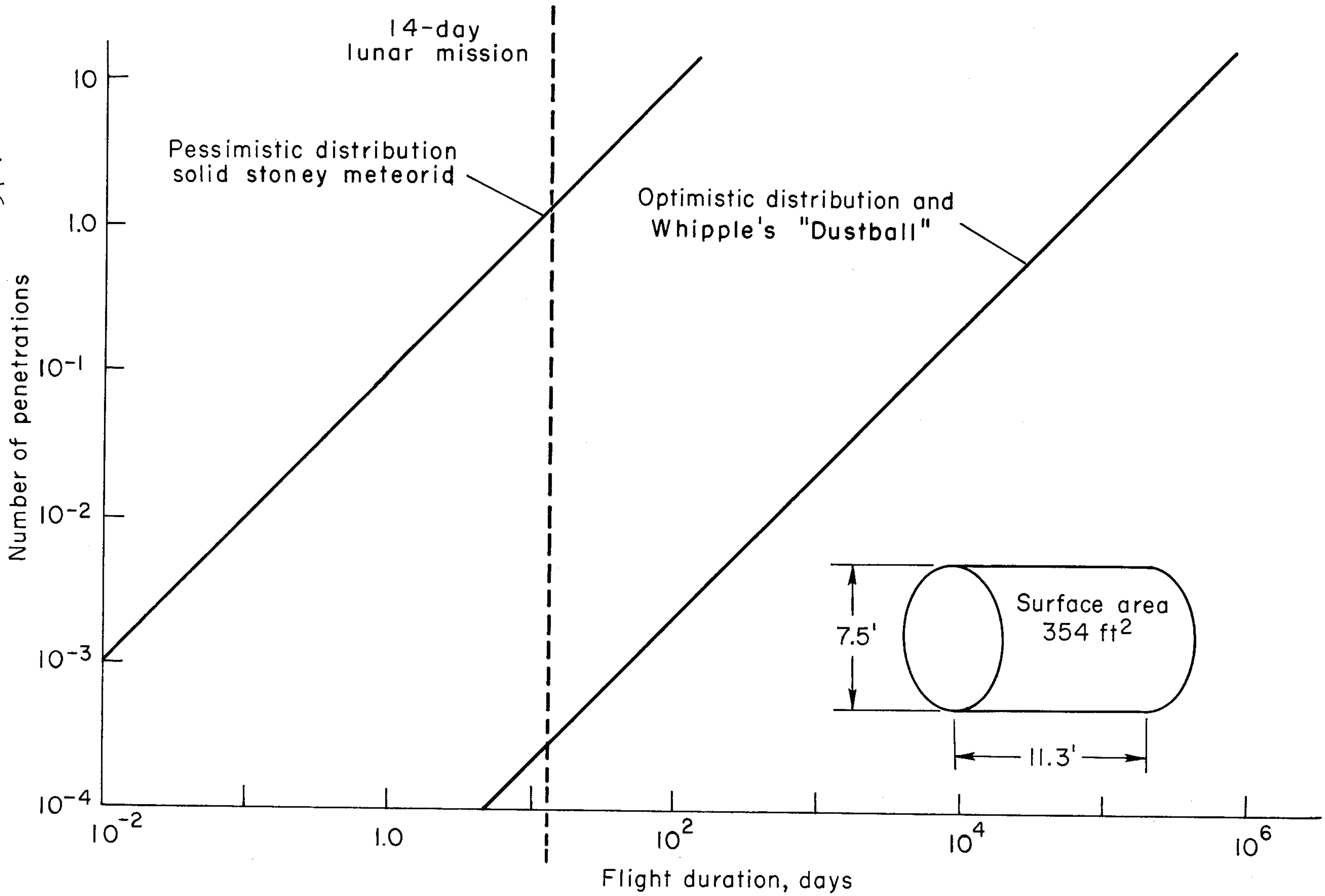

Figure 7.- Lunar vehicle with spaced, glass-wool-filled, double-sheet hull.

NASA TN D-1039
National Aeronautics and Space Administration.
PRELIMINARY INVESTIGATION OF IMPACT ON MULTIPLE-SHEET STRUCTURES AND AN EVALUATION OF THE METEOROID HAZARD TO SPACE VEHICLES. C. Robert Nysmith and James L. Summers. September 1961. 27p. OTS price, $0.75. (NASA TECHNICAL NOTE D-1039)

Small Pyrex glass spheres, representative of stoney meteoroids, were fired into 2024-T3 aluminum alclad multiple-sheet structures to evaluate the effectiveness of multisheet hull construction as a means of increasing the resistance of a spacecraft to meteoroid penetration. In addition, the meteoroid hazard to vehicles in the space near the earth is evaluated on the basis of the meteoroid distribution as determined from astronomical and satellite measurements, high-speed impact data, and hypothesized meteoroid structures and compositions for two representative space vehicle structures, one with a single-sheet monocoque

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